A TELEOPERATED FACILITY FOR VARIABLE GRAVITY LEVEL FLUID PHYSICS EXPERIMENTATION

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ABSTRACT

A facility to perform experiments on fluid physics and specially on the mechanical behavior of liquid bridges has been designed and built. The facility consists of a velocity controlled centrifuge than can be rotated at speeds up to 10 rpm with and arm of 1.5 m where the experiment container (a Plateau tank in which different mechanical stimuli can be imposed to the liquid column) can be fixed at any location. The rotating system transmits out a video signal for diagnosis and besides control and monitoring signals are routed to the external data management system. The facility and its control system has been implemented in a way that it is possible to control and monitor the experiments either locally from a control workstation or the entire facility can enter in a mode to be controlled remotely. In this case, the control workstation is located far away the facility (indeed in a different city) and linked with data lines. The purpose of this exercise is to gain experience on the minimum data bandwidth needed and the impact on orbital platforms fluid science experimentation of transmission delays and data loses. The latter effects are implemented in the data stream in a way that can be simulated at a rate much higher than that will be experienced otherwise.

INTRODUCTION

Liquid bridges occur in both natural and technological situations and have been studied for practical reasons and for basic scientific interest. In the simplest configuration a bridge consists of an isothermal drop of liquid held by surface tension forces between two parallel solid disks, as shown in Figure 1.

Disregarding additional electric and magnetic fields effects, the equilibrium interface shape of such a liquid bridge configuration is determined by the following dimensionless parameters:

- The slenderness, $\Lambda=L/(2R)$, where L is the distance between the supporting disks and $R = (R_1+R_2)/2$ is the mean radius.
- The ratio of the radius of the smaller disk to the radius of the larger one, $K = R_1/R_2$.
- The dimensionless eccentricity, $e = E/R$, $2E$ being the distance between the disk axes.
- The dimensionless volume, $V=V^*/(\pi R^2L)$ defined as the ratio of the actual volume V^* to the volume of a cylinder of the same length L and diameter R.
- The Bond number $B = \Delta\rho a R^2/\sigma$, where $\Delta\rho$ is the difference between the density of the liquid and the density of the surrounding medium and a is the acceleration acting on the liquid (whose axial and lateral components are $a_a = a\cos\alpha$ and $a_l = a\sin\alpha$, respectively).

The behavior, either static or dynamic, of a liquid bridge depends on the values of the above mentioned geometrical and volume dimensionless parameters as well as on the nature of the imposed perturbation (Bond number or other stimuli). Equilibrium shapes and stability limits of capillary liquid bridges have been investigated theoretically and experimentally for some time, and there is an extensive body of literature dealing with such fluid configurations (Meseguer *et al*., 1994, Meseguer *et al*., 1999).

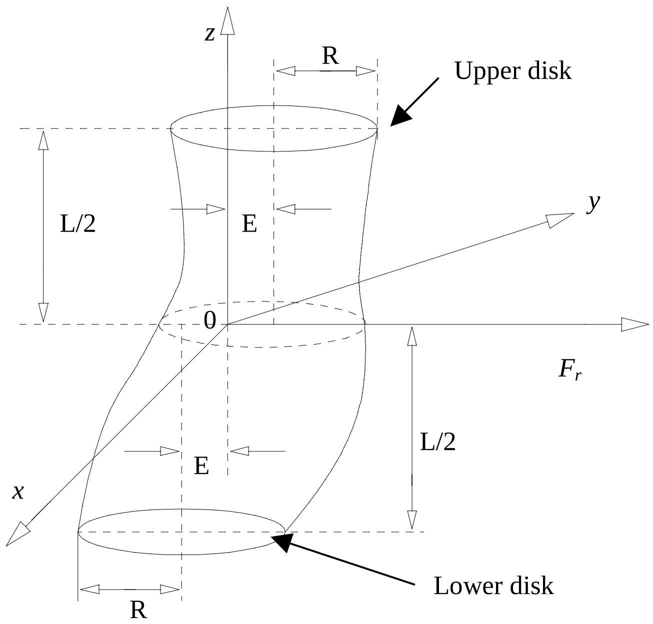

Fig. 1. Liquid bridge sketch showing relevant parameters

Most of the published papers deal with liquid bridges subjected to small Bond numbers. Since $B=\Delta\rho a R^2/\sigma$, it can be made small by reducing the acceleration a acting on the liquid column. This can be achieved in a free fall experiment (for example in a drop tower, on aircraft flying parabolic flight trajectories, in sounding rockets and on low-earth orbit platforms). The Bond number can also be reduced by matching the densities of the working liquid and the surrounding fluid (the Plateau or neutral buoyancy technique) or by using supporting disks with very small radius (micro or millimetric liquid bridges).

In the experimental facility described in the following the three aforementioned effects that contribute to the magnitude of the Bond number can be, within limits, independently controlled. In this facility, the neutral buoyancy technique is employed and $\Delta\rho$ is controlled by selecting the appropriate density of the surrounding fluid. Support disks of different diameters can be also used and the liquid column is mounted on a centrifuge so that the magnitude of the acceleration acting on the bridge can be adjusted by varying the rotation rate of the centrifuge. The accelerations to be accounted for are gravity, g, plus the centripetal one due to the solid-body rotation of the liquid bridge, $\Omega^2 r$, so that $a = (g^2+\Omega^4 r^2)^{1/2}$.

It must be pointed out that the Bond number is not constant along the liquid column. This is because the liquid bridge rotates as a solid body and the centripetal acceleration varies with the distance to the rotation axis. However, for particular conditions the effect of the Bond number gradient can be negligible (Zayas *et al*., 2000).

APPARATUS

The experimental facility, as sketched in Figure 2, consists of a liquid bridge cell mounted on a horizontal, rotating platform. The platform can rotate at any prescribed angular velocity within the range 0-1.05 rad.s^{-1} (0-10 rpm) with an accuracy of $\pm 2\times 10^{-3}$ rad.s^{-1} (±0.02 rpm). The rotating platform is a metallic beam 1.5 m in radius (A), mounted on a support structure (B) where the electric motor used to rotate the beam as well as the control electronics are located (C).

The rotating platform (A) supports the test box (D) as well as the data and commands transmission unit (E), which is located at the platform rotation axis. The test box consists of two rectangular plates with a hinge mounted on a common side (as sketched in the insert in Figure 2). One of the plates (D1) is attached to the rotating platform whereas the second one (D2) can be rotated at any prescribed angle with respect to D1. Presently, both the position of the plate D1 along the rotating arm and the angle between plates D1 and D2 are set manually (so that the rotation must be stopped to change these positions), although a new test box in which these position can be changed without stopping the rotating arm is now under development.

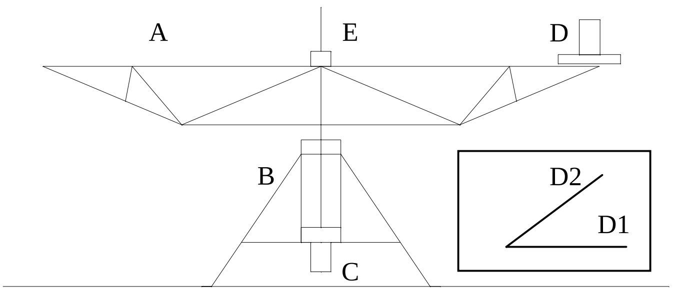

Fig. 2. Sketch of the experimental facility

Upper plate D2 supports the liquid bridge cell (LBC), the illumination system, a video camera to record the experiments, a set of batteries to power supply for the recording and illumination system, and a set of small containers with the fluids for the liquid bridge and the surrounding bath. To perform the experiments the so called neutral buoyancy or Plateau technique is used: the liquid column is formed inside another liquid (surrounding bath) of nearly the same density but immiscible with the former. Usually a dimethyl-silicone oil is used as the working liquid whereas for the surrounding bath a mixture of methanol and distilled water is used (since LBC test chamber is tight, no alcohol evaporation occurs, so that the surrounding bath density is constant).

Several liquid bridge cells have been developed. The simplest liquid bridge cell is a tight chamber connected to a calibrated syringe. In this case the LBC test chamber is a 0.04m×0.04m×0.04m aluminium cube, with two opposite faces made of a transparent, plastic material. This allows visualization of the liquid bridge. The liquid bridge is formed between two equal disks 0.01 m in diameter. One of the disks is connected to the piston of the syringe and can be displaced along its axis by using a micrometer screw. The remaining disk is fixed to the opposite side of the test chamber such that both disks remain in coaxial alignment whatever their separation distance. Liquid is injected and removed, using quick-disconnect valves, from the liquid bridge through a hole in the centre of the moving disk which connects it with the syringe. The diameter of the piston is equal to the diameter of the disks and the moving disk is mounted at one end of the piston syringe. Thus, the amount of liquid injected or removed when the disk is displaced causes the volume of the liquid column to be cylindrical within 0.1 % accuracy ($V = (1\pm0.001)2\pi\Lambda$) regardless of the distance separating the disks.

There are three different small containers in the system for fluids supply and disposal: one of them is used to supply the fluid to form the liquid bridge; the second one is used to supply the surrounding bath; and the third is used to recover the fluids from inside the test cell when occasionally the liquid bridge is broken in the experimentation process.

Observation system

To monitor the system performance an 8 mm CCD video camera video is used (Figure 3), together with a TV sender and a TV receiver. The video camera is installed in the platform that supports the test cell, with the optical axis aligned with the centre of the observation window, and the video output from the camera is connected to a small and low power TV emitter, located in the axis of the rotation arm. Omnidirectional antennae are used in the emitter and TV receiver in order to minimise the signal modulation caused by the rotation of the TV station inside the laboratory and, also, both pieces of equipment are battery powered.

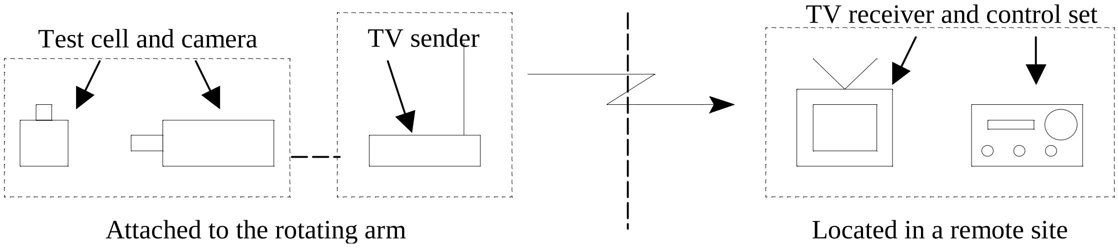

Fig. 3. Observation system schematics

Control System

The system has been devised to allow an easy change of mode of control from local (for setting-up and troubleshooting and debugging purposed) to remote (for analysing the impact of data bandwidth reduction and transmission delays in experiment performance and scientific return).

The different analogue signals coming from or going to the rotating table are digitised by an analogue to digital converter, and the video signal coming from the sender on board the rotating table is received and digitised by a frame grabber. Both the data acquisition board and the frame grabber are in installed in a PC and controlled by the software running on it (based in LabView). The inputs/outputs of the control software are redirected to a TCP/IP socket. This allows for an easy connection to the Man Machine Interface (MMI) which also sends and receives data via the same TCP/IP socket, so that the MMI software can run on the very same machine where the controller resides (this mode is used only for troubleshooting), in a machine next to the controller or remotely, without any change (Figure 4). The design also allows the introduction of random delays (just using the Internet as a transport system) or controlled delays by inserting a module to receive the TCP/IP packets and store them in a buffer for a while.

When the MMI is run in a PC close to the facility, a LAN is used, but for remote communications either the Internet or a dedicated ISDN connection can be used. If the Internet is used, bandwidth can oscillate widely, whilst the ISDN allows for a constant but reduced bandwidth.

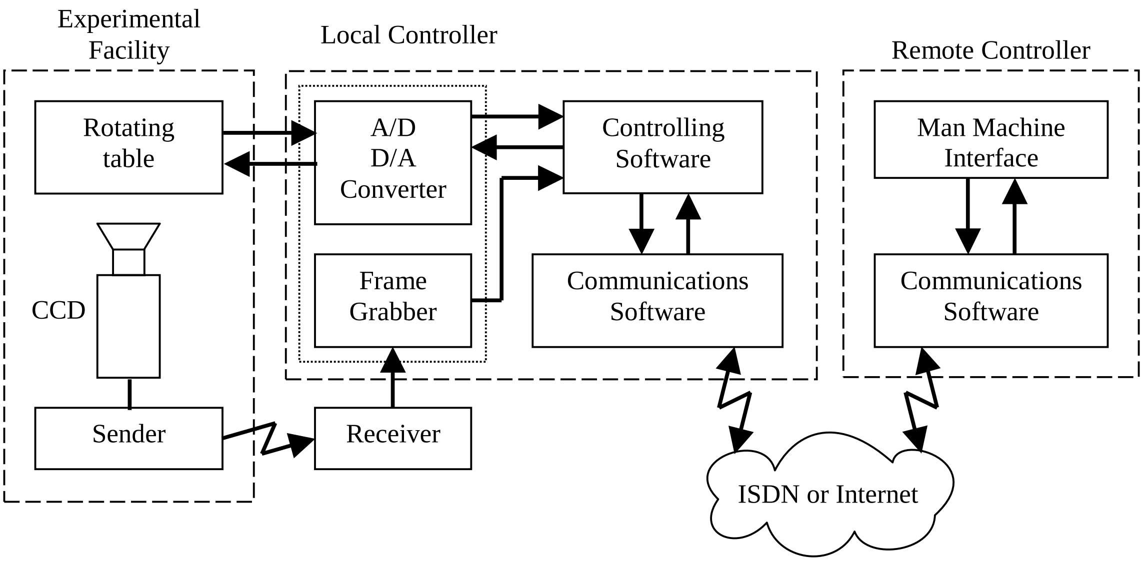

Fig. 4. Block diagram of the control system

CONCLUSIONS

A experimental facility for fluid science experimentation has been developed and a control system for it has been devised that allows easy operation either locally or remotely. The purpose of the remote control is to evaluate the impact on operations and scientific performance of the delays and reduced bandwidth of communications. The development is in the frame of preparing future operations of the experimental facilities on board the International Space Station. One of the experiment operation modes will be to interface with the experiment directly from the experimenter laboratory (User Home Base, UHB) connected with a data line (ISDN type) with the ground operations infrastructure. Obviously, the impact of this reduced bandwidth on operations directly from UHBs must be exercised before the actual experiment to evaluate the need of better communications or of operating the experiment directly from a centre with dedicated and better data lines (the so called Facility Responsible Centres, FRCs, and Facility Support Centres, FSCs.

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